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SUBJECT: CHOPPING SECONDARY MIRROR SPECIFICATIONS FOR SOFIA

1011 REVIEW

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An infrared optimized telescope uses a chopping secondary to switch the instrument beam back and forth between positions in the sky. This allows synchronous detection of signal from an astronomical source in parts of the spectrum where these observations are strongly background-limited by thermal emission from the telescope and the atmosphere. To most efficiently reject this fluctuating background, as well as detector noise, which has a 1/f character, the highest possible chop frequency is desired. To maximize the spatial dynamic range of the observations, the largest possible chop amplitude is desired. These parameters must be traded off against image degradation by the chopper system, which will limit our ability to measure the shape and extent of astronomical sources and, for background-limited measurements, will reduce signal strength in an otherwise optimally small bea

In order to make full use of the image quality of the telescope, the chopping secondary system should be capable of producing secondary motion that does not contribute substantially to the image size at every wavelength at which the telescope will be used. This is the primary goal of the specifications for the SOFIA secondary mirror system.

I. Bottom-line requirements: the least we should do

One of the great advances that will be possible with SOFIA will be the ability to measure the sizes of objects that are at least a factor of three smaller than can be measured with the KAO. In order to be able to measure the size of an astronomical object that is small compared with the intrinsic point source profile of the telescope (PSPT), a chop amplitude at least four times that of the FWHM of the PSPT is required. The system point source profile (PSP) is the convolution of the PSPT and the chopper point source profile (PSPC), which is just the spatial integral of the chop waveform (PSP=PSPT*PSPC).

In order to be able to distinguish an object that is extended on a scale of the PSPT, the chopper must degrade the PSP by less than 50%. At <30 microns, where the PSPT is dominated by optical imperfections and seeing at the 2" lev this requires a time-averaged chop profile that contributes <1" to the image siz for a chop amplitude of about 10". For a given chopper rise time, the image degradation can be expected to scale with chop amplitude. At wavelengths longward of 30 microns, where the PSPT is diffraction limited, we thus require that the chopper contribute less than 10% of the chop throw to the PSP. This is a bottom line performance limit, in the sense that a chopper inferior to this will not take advantage of the optical quality of SOFIA. In terms of the capabilities existing IR chopping secondary systems, this requirement is trivial to achieve, however.

II. Practical requirements: the best we can hope for?

The above bottom-line case is for a minimum spatial dynamic range, with a single detector looking at a compact source. Studies of morphologically complicated objects (star forming regions, galaxies, etc.) will require much larger spatial dynamic range, however, as will effective use of imaging arrays. A natural limit to the chopped image quality is set by the aberrations in the telescope. These aberrations scale with off-axis angle, in parallel with the aberrations produced by a chopper that is centered around the optical axis. Studies of the f/1.2 primary mirror system for SOFIA show that a limiting spatial dynamic range (ratio of off-axis chop displacement to chopped image size) is ~30. Thus, in the usual method of infrared observing, in which the chop is centered on the optical axis so that both chopped beams suffer the same amount of aberration, it is not necessary to construct a chopper with a PSPC much smaller than this.

The effect of the PSPC on the PSP would be most easily evaluated if the PSPC were gaussian, but it isn't even close to that shape (see Figures) and it's FWHM is therefore hard to define. We can talk about the effect of the PSPC on the PSP, however, by asking what size gaussian would be required to degrade the FWHM of the PSPT to that of the final PSP. We define this as the FWHM of the PSPC. This number is somewhat dependent on the PSP' that is used, and off axis coma on the PSPT is not really gaussian either, but can be evaluated for particular cases. Shown in the table below is the effect of two different chopper rise times, and the effect that each has on a PSPT of >8", which is about that expected for a +/-4' chop. This lower limit of the PSPT applies to short wavelengths, where the PSPT is dominated by optical aberrations rather than diffraction. The choice of the two rise times for which these calculations were made was beased on the performance achieved by the new Ball Aerospace chopper for the KAO. The PSP PSPC and PSPT for each of these cases are shown in Figure 1 and 2 as well. For simplicity, the PSPT was taken to be a gaussian. The 8" width of this gaussian was chosen to match the 86% image size for a +/-4' chop, and is very nearly the FWHM of the Airy disk at 100 microns.

Rise time is time to 1% of throw for overdamped oscillator.

Throw = 8' (+/-4')
Frequency = 35 Hz (maximum spec)
Efficiency is computed for boxcar aperture size with FWHM of PSPT (8")
(fraction of the time that the chopped source is in the aperture relative to an ideal chopper with delta function PSPC)

Rise time (ms)	FWHM in arcsec			Efficiency
	PSPT	PSPT*PSPC	PSPC	
5 ms	8"	8.7"	3"	0.7
10 ms	8"	11.7"	8"	0.3

This table shows that for achievable rise times, the contribution of the chopper (PSPC) to the images on SOFIA (PSPT*PSPC) is similar to that of the optical image quality of the telescope itself at that chop throw. For a chopper rise time larger than 10ms, the chopper, rather than the optical aberrations, will dominate the image FWHM. Since the FWHM of the PSPT PSPT scales roughly linearly with chop offset, and the PSPC does too, the listed rise times should satisfy this condition for a wide range of chop throws. While the FWHM image degradation with a 10ms rise time is not very serious, it is evident from the table that the efficiency of the system starts to suffer very quickly as the rise time increases above 5ms at the limiting chop frequency (see below). The efficiency obviously becomes essentially zero when as the rise time approaches 1/2f. These calculations suggest that a rise time of 8ms or less is highly desireable.

Since the largest chop throws are usually used by those observers with the longest wavelength system, with the largest diffraction limited beam (PSPT), we can compromise on the chop performance by derating the specifications for the largest chop throws, and highest frequencies. This will serve to limit the peak power requirements of the actuator drivers, and the total power dissipation of the system. It will also limit the extent to which the chopper drives mechanical modes on the telescope. Based on the BASD chopper for the KAO, we can adopt as a target goal a 5ms rise time for 0-4' chop, derated to 8ms for larger chops, with chop frequency > 20Hz.

III. Requirements for chop stability

It is important to distinguish the separate specifications on chopper stability and time averaged chop profile. Much more stringent requirements are set by pointing stability requirements of certain experiments, and the the desire to do superresolution imaging. Pointing stability at the 0.2" level is needed for FTS spectrometers, in which fluctuations produced by an object moving around in the beam during the course of an integration limit the sensitivity. For observations at visual wavelengths, in which the secondary will be held stationary by the chopper mechanism (zero amplitude) a similar level of stability is required in order to satisfy the basic pointing stability spec for the telescope. For the FTS experiment, "stability" refers to a time scale that is long compared with the time required to scan the spectrum of an object, which may be several minutes, if tracker tracking is being used. If focal plane tracking is being used, then this "stability" refers to a time scale that is long compared with the bandwidth of the tracker (which may be several seconds, depending on the gyro drift rate).

Superresolution techniques have been demonstrated in which gains of a factor of three over that of the diffraction limited PSPT have been achieved. Simple gaussian deconvolution arguments can be made that suggest that the time averaged PSPC be stable on a spatial scale that is half that of the spatial scale that we want to deconvolve. Thus, for a superresolution gain of three at 30 microns, which is the shortest wavelength at which the telescope is diffraction limited, the PSPC must be stable and well determined at the 1.2" level (lam/2D) to get diffraction limited information about the source from the image. To get a gain factor of three, the PSPC must be stable and well determined at the 0.4" level, which is similar to that which is required by FTS experiments. In a superresolution experiment "stability" refers to a time scale that is long compared to the time between when the program source is observed, and the time that the PSP is determined on some bona fide point-like astronomical source. This time scale may be a substantial fraction of a flight duration and ideally would apply to all flights in a particular flight series. In general, the highest possible spatial resolution will be associated with the smallest possible chops, allowing us to derate this spec to the larger of 0.2" or 1% of throw.

IV. Chop throw requirements

The maximum chop throw of 10' (+/-5') will give a spatial dynamic range that i several times higher than that achievable on the KAO. By matching the chop amplitude obtainable on the KAO during most of its lifetime, regions can be surveyed in a comparable way, if necessary. This large amplitude will allow SOFIA to overlap with the spatial scale achieved by IRAS at all survey wavelengths. It should be possible to decenter the chop relative to the optical axis anywhere within this range. With a nominal tilt gain of 0.25, this requires that the mirror be able to tilt over a range of 40'.

V. Frequency range requirements

The maximum chop frequency is not a fundamental specification for the chopper, since the external inputs to the chopper drive will, in principle, allow any chop frequency to be produced. The chop frequency does, however, enter into the chopper definition through the actuator power dissipation and the efficiency (defined above). The lower limit for the chop frequency is zero, though background-limited measurements will probably need to stay above the baseline 8Hz servo bandwidth of the telescope in order to avoid noise due to scattered or diffracted background from the cavity. At the high frequency end, the background limted observer will want to stay below the lowest resonant frequency of the telescope structure, at which there will be noise power due to the telescope moving around relative to the instrument beam. The latter is estimated to be ~40Hz (dumbbell mode). It is also important to avoid driving any telescope structural mode by the chopper, and the high bandwidth of the chopper system (several hundred Hz) requires that the interaction of the chopper and telescope structure be examined more closely.

VI. Focus requirements

The secondary mirror will be moveable along the optical axis to focus the telescope. The range of travel will be set by the focal plane instrument accomodation specifications. Using a nominal value of 50cm for the required focus range, and a nominal focal plane/secondary translation gain of 307, we require that the secondary travel be at least 1.6mm. This number should be adjusted upward to include the effects of thermal contraction of the telescope structure. It is important that all instruments within the specified focal position range can be brought into focus on the ground as well as in the air without adjustment of the spider.

It is necessary that the focus resolution of the secondary be commensurate with the highest image quality of the telescope. While seeing effects will degrade the actual image quality somewhat, the liklihood that the telescope will be used in a speckle mode requires that the focus resolution be matched to the intrinsic image quality of the optics. With a specified 86% image FWHM of 1", we require a blur circle resolution of better than 0.5". At f/22, with 3.8"/mm, this corresponds to <0.13mm, or <2.9mm along the optical axis. This translates to a resolution at the secondary of <9 microns. In order to give the most flexibility to those users that will need the highest possible spatial resolution at visual wavelengths, and in order to best take advantage of special improvements in the optical image quality (such as active adaptive optics) that may be implemented at a later date, we request that the secondary drive be movable at twice this minimum resolution (4 microns).

Temperature changes from ground-air, as well as along the flight path will cause the telescope focus to change slowly. In order to maintain the highest possible image quality in a reasonably time efficient way, an automatic way of refocussing the telescope using the focal plane image will most likely be implemented. This will require an external input to the focus drive, as well as push buttons on the control panel. The focus position should be encoded, at this level.

VII. The case for an XY (2-axis) chopper

For the new KAO chopper, Ball Aerospace decided that an XY chopper could best meet the rise time specifications, and yet be able to chop in any direction, which is important to several kinds of work. This differs from the radial chopper that is common on most infrared telescopes. Their decision to do this was based on the lack of stiffness in a central, slowly rotatable hub. Operationally, there are advantages and disadvantages to an XY chopper. In addition to the structural advantages, an XY chopper can switch chop direction very quickly. The ability to quickly manipulate the center of the chop in two directions makes optical alignment very convenient, and this has been taken advantage of already on the KAO. The ability to slew the beam around in any pattern may be advantageous for work with arrays, and the ~200Hz bandwidth of the system opens up the possibility of doing image motion compensation without additional optics. These factors lead to the further requirement that the chopper be drivable by external inputs that are summed with the chop waveform. The main disadvantage of an XY chopper is that unless the orthogonal actuators are precisely matched, the chop waveform will be dependent somewhat on chop angle and, at angles at which both axes are active, the trace between the two beam positions is not necessarily a straight line. This is not expected to be a serious problem, however.